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# Ambitious environmental and economic goals for the future of agriculture are unequally achieved by innovative cropping systems

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## Abstract

Agriculture has to face huge challenges in the decades ahead. Four innovative cropping systems were assessed in a "cropping system experiment" in the Ile-de-France region (France) from 2009 to 2014. Three were designed to meet ambitious goals: the total elimination of pesticides (No-Pest), reducing fossil energy consumption by 50% (L-EN), or decreasing greenhouse gas (GHG) emissions by 50% (L-GHG). They were also required to satisfy a wide range of environmental criteria and to maximize yields whilst respecting the major constraint on the system and the environmental targets set. A fourth system (PHEP), in which the environmental and yield targets were achieved with no major constraint, was also assessed. After completion of the first full crop sequence for these innovative systems, the results obtained indicated that it was possible to design and implement innovative systems achieving multiple goals. In our field trial conditions, the pesticide and energy constraints were almost satisfied, whereas the GHG target was missed by a considerable margin. All four innovative systems satisfied environmental criteria in terms of N management, pesticide use, energy consumption and crop diversity. However, herbicide treatment frequency index (TFIH) was higher than expected in the two systems with no-plow practices, L-EN and L-GHG. In the pesticide-free system, soil organic matter content was lower than expected, due to frequent plowing (every 2 years) and low residue levels as a result of the lower yields obtained. Yields were lower for the L-EN system than for the reference system, and yield was variable in the L-GHG system. These innovative systems had better environmental performances than the systems currently used in the Ile-de-France region, with no decrease in gross margins.

Key words: cropping system experiment, field assessment, greenhouse gas emissions, pesticide, energy.

## 1. Introduction

New challenges are continually arising in agriculture, necessitating profound breakthrough innovations in agricultural practices. The most serious issues faced concern: (1) the loss of biodiversity in agroecosystems, (2) the need to reduce chemical inputs, which are known to be harmful to the environment and human health, and (3) the need to decrease the impact of agriculture on climate change, by decreasing greenhouse gas emissions and promoting carbon storage in the soil. Current arable cropping systems are of questionable sustainability, and alternative cropping systems must therefore be designed, to meet the goals of a more sustainable agriculture. Agronomists design and assess innovative cropping systems to tackle a wide range of issues (Doré *et al.*, 2011; Blazy *et al.*, 2009; Sadok *et al.*, 2009). Moreover, given that global food security has become a primary concern (Godfray *et al.*, 2010), there is a need for innovative cropping systems that increase agricultural resource use efficiency (Foley *et al.*, 2011).

New strategies for crop management and new cropping systems have been designed in recent years. Many have targeted a single principal goal, such as enhancing C sequestration through changes in crop management (*e.g.,* Freibauer *et al.*, 2004; Dimissi *et al.,* 2014), reducing pesticide use (Aubertot *et al.*, 2005; Chikowo *et al.*, 2009), decreasing energy consumption (Singh *et al.*, 2008; Khakbazan *et al.*, 2009), or improving the yield of a single crop (Tapia *et al.,* 2014). However, some studies were "innovation-pushed": the authors compared cropping systems on the basis of the combination of agricultural practices used (Kulak *et al.*, 2015), rather than on the achievement of target performances with the most appropriate practices. For example, they compared organic and conventional systems (Panasiewiez *et al.,* 2010; Nemecek *et al.*, 2011a), or no-tillage and conventional tillage systems (Abdi *et al.*, 2014; Dimissi *et al.*, 2014), without providing any further information about the objectives to be reached. In most of these examples, only a few criteria were assessed in field trials: the distribution of phosphorus species in the soil profile (Abdi *et al.*, 2014), changes in soil structure and yield performances (Abdollahi *et al.*, 2015), soil biological properties (Ingle *et al.,* 2014), ecophysiological characteristics of spring barley and genotypes under various systems (Panasiewiez *et al.*, 2010), and weed infestation under different long-term tillage systems (Chikowo *et al.*, 2009). However, in some cases, multi-criteria analyses were performed, with various methodologies (Nemecek *et al.*, 2011a, 2011b; Loyce *et al.*, 2012; Kulak *et al.,* 2015). These multi-criteria assessments made it possible to analyze combinations of agricultural practices with opposite impacts on specific criteria, and to consider trade-offs. For example, no-till systems decrease energy consumption, but increase herbicide use (Zentner *et al.*, 2004).

To our knowledge, no study has yet both (i) designed *in silico* innovative and consistent cropping systems addressing a multiplicity of current issues, and (ii) assessed them in a cropping system experiment involving the analysis of multiple performances. We designed *in silico* innovative cropping systems addressing multiple issues of importance (Colnenne-David and Doré, 2015a), and conducted system experiments to assess their ability to achieve several goals. Four innovative cropping systems targeting various environmental goals and yield objectives were designed by the prototyping method described by Vereijken (1997). Their performances were assessed *ex ante* with various tools and models: the Indigo® method (www7.inra.fr/indigo) for environmental performances, the Simeos® tool (using the AMG model, Andriulo *et al.*, 1999) and the Roth C model for carbon sequestration, as in the study by Colnenne-David and Doré, 2015a. For each combination of objectives, the most promising candidate system was then implemented in a cropping system experiment.

We present here the cropping system experiment results for these four innovative cropping systems, for the first full crop sequence. We analyzed the performance of the cropping systems in several different ways: (1) we compared the innovative cropping systems implemented in the field trial with the prototypes (Colnenne-David and Doré, 2015a); (2) we compared the three innovative systems designed to meet particular constraints with a constraint-free innovative system used as the reference system and (3) we compared the innovative systems and the current system in the Ile-de-France region, where the field trial took place.

## 2. Materials and methods

### 2.1. General description of the four innovative cropping systems

Four innovative cropping systems with quantified constraints, and environmental and yield targets were designed jointly with various stakeholders, including farmers, in 2008 (table 1, Colnenne-David and Doré, 2015a). The "productive with high environmental performance" (PHEP) system was designed to minimize environmental impact (decreasing nitrate and pesticide pollution, enhancing crop diversity or reducing fossil energy consumption relative to current cropping systems) and to reach the maximum possible yield given the environmental targets, as described by Colnenne-David and Doré, 2015a. This cropping system, which was designed without major environmental constraints, was used as the reference system for comparisons with the other systems. Each of the other three systems was designed to meet an additional environmental constraint, constituting a major breakthrough in terms of the objectives for current cropping systems: the elimination of pesticide use (No-Pest), reducing fossil energy consumption by 50% relative to the PHEP system (L-EN), or halving greenhouse gas emissions relative to the PHEP system (L-GHG). These cropping systems were also designed to minimize environmental impact whilst providing the maximum possible yield under the constraint imposed and respecting the environmental targets. During the design step, the constraints and targets were prioritized as follows: the environmental constraint had to be satisfied first, the set of other environmental targets then had to be attained, and, finally, yield had to be maximized. The systems retained for field assessment corresponded to the combination of agricultural practices resulting in the highest yields *in silico* among the candidate systems both satisfying environmental constraints and meeting environmental targets.

## 2.2. Main agronomic characteristics of the four innovative cropping systems

The four cropping systems were based on the agronomic strategies described in table 1 (Colnenne-David and Doré, 2015a).

## 2.3. Experimental trial

Since 2008, the innovative cropping systems have been implemented in a cropping system experiment, located at the AgroParisTech experimental farm at Grignon, in the Ile-de-France region (*i.e.* Paris Basin, N 48.84°, E 1.95°). This site has a deep, homogeneous loamy clay soil (FAO, 1998). Mean annual rainfall, calculated over a 20-year period was about 650 mm per year at this site. The crop immediately preceding this experiment was winter barley and the field had been plowed (30 cm depth). The trial covered a total area of 6.2 ha, divided into large plots (almost 4000 m²) to facilitate the rational use of farm machinery in conditions representative of those on farms. Due to both the limited area available for the trial and the need for large plots, each system was randomly distributed in a block design with only three replicates. The size of the trial was such that we were unable to grow all of the crops of each crop sequence in each innovative system each year. The interannual variability results were taken into account by sowing three different crops from the crop sequence of each system in the three replicates for the year concerned, for each of the innovative systems (*e.g.* in 2009, winter wheat, winter oilseed rape and spring barley were sown in the three different replicates of the PHEP system). The first full crop sequence covered the 2009-2014 period: five successive crops for the PHEP and L-EN systems (2009-2013), and six for the No-Pest and L-GHG systems (2009-2014).

## 2.4. Measurements

### 2.4. 1. Calculation of indicators

Assessment of the environmental performance of the cropping systems was based on energy consumption, GHG emissions, C sequestration and various environmental criteria, for real practices in the cropping system experiment. Each environmental indicator was calculated over an entire crop sequence, and expressed on a per hectare and per year basis. Criter® software (V4.0.), based on the Indigo® method and easy to manage, was used to calculate a set of environmental indicators taking values of 1 (worst) to 10 (best), with 7 selected as the target value for the entire crop sequence (Bockstaller *et al.*, 2009; Reau *et al.*, 2012).

### 2.4.2. Pesticide indicators

Three pesticide indicators provided qualitative information about the volatilization, runoff and leaching into groundwater of pesticides, thereby providing an indication of potential environmental damage. The treatment frequency index (TFI), developed by Gravesen (2003) and widely used to assess cropping systems in France (Ecophyto R&D, 2011; Jacquet *et al.*, 2011), was also calculated, to assess the intensity of pesticide (fungicides, herbicides, insecticides, molluscicides) use. This index takes into account the number of pesticide applications and the amounts applied. For each crop, TFI was calculated as follows: $\mathrm{TFI} = \sum_{\mathrm{T}} {}^{\mathrm{AD}_{\mathrm{T}}}/_{\mathrm{RD}_{\mathrm{T}}}$, where T is the pesticide application, AD is the amount applied per hectare (l.ha$^{-1}$ or kg.ha$^{-1}$) and RD is the amount authorized per hectare (l.ha$^{-1}$ or kg.ha$^{-1}$) (OECD http://www.oecd.org/site/worldforum/33703867.pdf; Pingault *et al.*, 2009). The recommended doses were those indicated in the E-phy database of the French Ministry of Agriculture (Ephy website, 2014). This indicator describes pesticide use through a single synthetic variable, facilitating comparison between systems. TFI, TFIH and "TFI others" correspond to overall pesticide use, herbicide use and the use of fungicides plus insecticides plus molluscicides, respectively. Neither growth regulators nor nematicides were sprayed on crops.

### 2.4.3. Energy consumption, energy output and energy use efficiency

Energy consumption was assessed with the GES'TIM database (2010). Direct and indirect non-renewable energy consumption (*i.e.* energy inputs, EI, expressed in MJ.ha$^{-1}$.year$^{-1}$) corresponded to the fuel, lubricants and electricity used to power farm machinery and tractors. Indirect energy consumption was defined as the energy used in the manufacture, formulation, packaging and maintenance of inputs, such as machinery, fertilizers and pesticides.

Energy outputs (EO, expressed in $MJ.ha^{-1}.year^{-1}$) were calculated as the gross energy content of the harvested products. This indicator was calculated for each crop in each year, as follows: EO = Y * CV, where Y is the yield of the harvested crop ($t.ha^{-1}$), and CV is its calorific value ($MJ.t^{-1}$). Yield values were calculated as the mean of six samples (each from an area of 75 to 140 m², depending on the length of the plot harvested) collected at maturity with a combine harvester from each plot. CV was assessed with the GES'TIM database (2010). Energy use efficiency (EUE) was calculated by dividing EO by EI for the whole cropping system.

### 2.4.4. Carbon balance

Carbon balance ($kgCO_2eq.ha^{-1}.year^{-1}$) was calculated taking both C sequestration in the soil and total GHG emissions into account. C sequestration in the soil ($kgCO_2eq.ha^{-1}.year^{-1}$) was assessed with the Simeos® tool (2014), as recommended by Saffih-Hdadi and Mary (2008), and climatic data from a meteorological station located 150 m from the trial. The soil characteristics of the plowed layer (0–30 cm) used for the calculations were as follows: clay content 20.6%, silt content 71.9%, sand content 7.4%, bulk density 1.4, initial C content 13 $g.kg^{-1}$ dry matter, typical of soils in the Ile-de-France region. Annual yields, calculated from our experimental data, were used to estimate the expected annual biomass separately for the residues above and below the ground. Direct and indirect GHG emissions were estimated with the GES'TIM database (2010), with Intergovernmental Panel on Climate Change coefficients, focusing on two main greenhouse gases: nitrous oxide ($N_2O$) and carbon dioxide ($CO_2$). Direct emissions included $N_2O$ emissions from N fertilizers and the $CO_2$ produced by the combustion of fossil fuels by farm machinery. The $CO_2$ respired by soil organisms was not taken into account in these assessments. Indirect emissions corresponded to the use of fossil energy in the manufacture and maintenance of farm inputs.

Carbon balance was calculated over a period of 50 years, in accordance with Intergovernmental Panel on Climate Change proposals and current knowledge of C sequestration kinetics in the soil. In this calculation, any GHG entering the cropping system was attributed a negative value, whereas GHG leaving the system took a positive value. The overall balance was therefore positive if more GHGs were emitted than sequestered in the system.

### 2.4.5. Nitrogen indicators

Three nitrogen indicators were calculated with the Criter® tool (v. 4.0.). Two of these indicators provided qualitative information about ammonia ($NH_3$) volatilization and $N_2O$ emissions. $NH_3$ volatilization was assessed for each fertilizer type, set of soil chemical characteristics (specifically calcium content) and fertilizer burial status.

$N_2O$ emissions were calculated as described by Bouwman *et al.* (1996): the emission factor was 1.25% $N_2O$-N per kg N of spread mineral fertilizer. The target value for this indicator (*i.e.* 7) corresponds to 20 kg of $NH_3$ volatilized per hectare and per year, and 3 kg of $N_2O$ emissions per hectare and per year. Nitrogen leaching into groundwater was also assessed with the Criter® tool (v. 4.0.), and expressed as a quantitative value ($kgNO_3^-.ha^{-1}.year^{-1}$). The assessment took into account both the amount of fertilizer applied and the date of the application, together with rainfall over the leaching periods, from the end of winter until summer and during the winter season after crop harvest (i.e. from 01/08 to 31/03 at Grignon).

### 2.4.6. Crop diversity indicator

This indicator takes into account both the number of different species sown in the crop sequence, and the number of genotypes for each species included in the crop sequence. It is calculated at the scale of a full crop sequence. The contribution of catch crops is halved, as their growth period is shorter than that of the main crop (Criter® software, V4.0).

### 2.4.7. Economic indicators

We took the variability of prices and costs over time into account, by calculating mean values for France for the 2005-2012 period (INSEE). Changes in CAP (Common Agricultural Policy) directives resulted in CAP subsidies being based on a shorter period in 2010-2012. These subsidies averaged €325 $ha^{-1}.year^{-1}$ in the Yvelines, the area in which this trial was located. Gross outputs ($€.ha^{-1}$) were calculated by multiplying yield ($t.ha^{-1}$) by the farm-gate price ($€.t^{-1}$) received for harvest products. Total variable costs ($€.ha^{-1}$) included total input costs (*e.g.* mineral fertilizer, seeds, pesticides) and machinery costs (*e.g.* machinery maintenance, fuel, labor for operations). The costs per hectare of different operations were determined from the data in a published database specific to North-Eastern France in 2013. Price variability was taken into account by calculating mean fuel price (€0.8 $l^{-1}$) over the 2008-2013 period. Gross margins ($€.ha^{-1}$) were calculated as the difference between "gross outputs plus CAP subsidies" and total variable costs.

## 2.5. Three comparisons of cropping system performances

The performances of the innovative cropping systems implemented in the field trial were first compared with that of the prototype (the prototype characteristics were described by Colnenne-David and Doré, 2015a) in a multi-criteria analysis for each innovative system (*i.e.* for each innovative system and for each performance, ratios were calculated as follows: *ex post* performance /*ex ante* performance). The performances of the three innovative systems subject to constraint (the No-Pest, L-EN and L-GHG systems) were also compared to those of the PHEP system, by calculating ratios as follows: for each innovative system under constraint and for each performance, performance in the innovative system under constraint /performance of the PHEP system. Finally, performance ratios were calculated for the four innovative systems relative to the current system in the Ile-de-France region, defined on the basis of the data collected in 2006 (Agreste, https://agreste.agriculture;gouv.fr/; Colnenne-David and Doré, 2015a) (*i.e.* for each innovative system (the PHEP, No-Pest, L-EN and L-GHG systems) and for each performance, ratios were calculated as follows: performance of the innovative system /performance of the current system in the Ile-de-France region).

### 2.6. Statistical and multi-criteria analyses

The performance and yield data were analyzed with by comparing means and carrying out analysis of variance (ANOVA) with R statistical core software (R Development Core Team R, 2014). If the result was significant ($p<0.05$), the Tukey test for multiple comparisons was performed, for means with a *p-value* of 0.05 or less. When the variance was zero (*e.g.* the TFI values of all replicates of the No-Pest system were zero), only the confidence intervals ($p<0.05$) were calculated.

## 3. Results

### 3.1. Assessment of the environmental performance of cropping systems

### 3.1.1. Pesticide use

### 3.1.1.1 The pesticide constraint in the No-Pest cropping system: comparison between the No-Pest and PHEP systems

The pesticide constraint was satisfied because no pesticides were applied in the No-Pest cropping system.

### 3.1.1.2. Pesticide use in the four innovative cropping systems

The values of zero obtained for TFI, TFIH and TFIothers in the No-Pest system were significantly lower ($p<0.05$) than those calculated for the other three innovative systems (table 2). TFI values were not significantly different ($p<0.05$) between the three systems using pesticides (*i.e.* the PHEP, L-GHG and L-EN systems). In our experimental conditions, the association of no-plow practices with flax crops resulted in the highest levels of herbicide use, with significantly higher TFIH values for the L-EN system than for the other three systems (TFIH values for the various systems: L-EN=2.03; L-GHG=1.67; PHEP=1.23; No-Pest=0). Moreover, TFIothers was significantly higher in the L-GHG system than in the other three systems (TFIothers values for the various systems: L-GHG=1.01; PHEP=0.70; L-EN=0.35; No-Pest=0). Crop residues were not buried, and molluscicides were more frequently required for slug control than in the other systems (0.5 treatments per year in the L-GHG system, versus 0.2 and 0.1 treatments per year in the PHEP and L-EN systems, respectively). The inclusion of winter oilseed rape in the crop sequence resulted in higher levels of fungicide use: 0.3 treatments per year were applied in both the L-GHG and PHEP systems, whereas no fungicide was applied in either the L-EN or the No-Pest system (details in table 3). Overall, "TFIothers" values, which included data for fungicides, were low, due to climatic conditions unfavorable for disease development over the 2009-2014 period (Agreste, 2014).

### 3.1.2. Energy use

#### 3.1.2.1. The energy constraint in the L-EN cropping system: comparison between the L-EN and PHEP systems

Mean total fossil energy consumption (direct and indirect energy) was 7755 ± 711 MJ.ha$^{-1}$.year$^{-1}$ for the PHEP system and 5201 ± 502 MJ.ha$^{-1}$.year$^{-1}$ for the L-EN system; energy consumption was thus 33% lower for the L-EN system (table 4). The energy constraint target (half the energy consumption of the PHEP system) was therefore not met, although the decrease was nevertheless considerable. Indirect energy consumption, which accounted for almost 50% of total energy consumption in both cropping systems, was 37% lower in the L-EN system (2584 ± 479 MJ.ha$^{-1}$.year$^{-1}$) than in the PHEP system (4090 ± 489 MJ.ha$^{-1}$.year$^{-1}$). The mean amounts of N fertilizer, the largest contributor to indirect energy consumption, were 19 kgN.ha$^{-1}$.year$^{-1}$ for the L-EN system and 56 kgN.ha$^{-1}$.year$^{-1}$ for the PHEP system (table 3). Direct energy consumption, defined as energy used exclusively by farm machinery (*i.e.* for plowing, tillage, sowing, fertilization, crop protection and harvest, table 3), was 29% lower in the L-EN system (2618 ± 171 MJ.ha$^{-1}$.year$^{-1}$) than in the PHEP system (3665 ± 223 MJ.ha$^{-1}$.year$^{-1}$), mostly due to direct drilling and the absence of tillage.

#### 3.1.2.2. Energy performance of the four innovative cropping systems

Total energy consumption was not significantly different in the PHEP (7755 ± 711 MJ.ha$^{-1}$.year$^{-1}$), No-Pest (7604 ± 517 MJ.ha$^{-1}$.year$^{-1}$) and L-GHG (7459 ± 793 MJ.ha$^{-1}$.year$^{-1}$) systems and was significantly higher than that in the L-EN system (5201 ± 502 MJ.ha$^{-1}$.year$^{-1}$, $p<0.05$). A similar pattern was observed for both indirect and direct energy consumption (*i.e.* lowest values for the L-EN system, $p<0.05$, table 4). An analysis of energy components revealed differences between systems. In the No-Pest system, direct energy consumption was significantly higher

(4417 ± 425 $MJ.ha^{-1}.year^{-1}$, $p<0.05$) than that in the other systems, due to the large number of plowings (four plowings over the six-year crop sequence, table 3). The indirect energy consumption linked to fertilization (table 3) was significantly greater in the PHEP (4090 ± 489 $MJ.ha^{-1}.year^{-1}$, $p<0.05$) and L-GHG (4897 ± 568 $MJ.ha^{-1}.year^{-1}$, $p<0.05$) systems than in the other two systems (the No-Pest system: 3187 ± 99 $MJ.ha^{-1}.year^{-1}$, the L-EN system: 2584 ± 479 $MJ.ha^{-1}.year^{-1}$, table 4).

The L-EN system generated significantly less energy than the other systems (70997 ± 9991 $MJ.ha^{-1}.year^{-1}$, $p<0.05$, table 4). The high degree of variability of the energy output of this system was linked to the low winter wheat yield in 2012 (yield of 0.75 $t.ha^{-1}$, replicate 3, table 5), due to the development of highly competitive white clover. In the No-Pest system, despite low yields for most crops, energy output was high (103323 ± 3629 $MJ.ha^{-1}.year^{-1}$), due to the production of hemp (mean yield value of 11.23 $t.ha^{-1}$, table 5, with a calorific value of 1.65 $MJ.t^{-1}$). However, it was not significantly different from that calculated for the PHEP (95965 ± 8397 $MJ.ha^{-1}.year^{-1}$, $p<0.05$) and L-GHG (90229 ± 5572 $MJ.ha^{-1}.year^{-1}$, $p<0.05$) systems.

The higher energy use efficiency of the No-Pest system (13.61 ± 0.54, ns) than of the L-GHG system (12.14 ± 0.74, ns) resulted principally from its higher energy output, with no significant difference in the total energy consumption of these two systems (table 4). The energy efficiency value of the L-EN system was high (13.71 ± 2.10), but not significantly different from the other systems, due to the high level of energy output variability for the L-EN system (70997 ± 9991 $MJ.ha^{-1}.year^{-1}$, table 4).

### 3.1.3. Carbon balance performance

#### 3.1.3.1. The carbon balance constraint in the L-GHG cropping system: comparison between the L-GHG and PHEP systems

The carbon balances of the L-GHG (1202 ± 86 $kgCO_2eq.ha^{-1}.year^{-1}$) and PHEP (1188 ± 270 $kgCO_2eq.ha^{-1}.year^{-1}$) systems were not significantly different ($p<0.05$, table 6). The carbon balance constraint (halving the emissions relative to the PHEP system) was not, therefore, achieved. For both systems, total greenhouse gas emissions and C sequestration accounted for nearly 90% and 10% of the carbon balance, respectively. There was no significant difference between these two systems in terms of total, direct and indirect greenhouse gas emissions ($p<0.05$, table 6), resulting in similar ratios of direct and indirect greenhouse gas emissions for the two systems. The difference in direct greenhouse gas emissions between the L-GHG (541 ± 102 $kgCO_2eq.ha^{-1}.year^{-1}$) and PHEP (622 ± 82

$kgCO_2eq.ha^{-1}.year^{-1}$) systems was linked to an absence of plowing and only a few shallow tillage operations in the L-GHG system, whereas the plot was plowed once and subjected to numerous shallow tillage operations over the course of the crop sequence in the PHEP system (table 3). In the L-GHG system, indirect greenhouse gas emissions (511 ± 82 $kgCO_2eq.ha^{-1}.year^{-1}$) were higher due to the high seed requirement: (1) the number of seeds sown in no-plow conditions was systematically greater than that sown in current systems, in accordance with technical references, (2) emergence failure was observed for winter rapeseed in 2009 and 2014, and for maize and spring field beans in 2011, leading to a second sowing, and (3) cover crops were sown systematically each year (table 3).

After the first crop sequence, C sequestration was -149 ± 117 $kgCO_2eq.ha^{-1}.year^{-1}$ for the L-GHG system and -117 ± 150 $kgCO_2eq.ha^{-1}.year^{-1}$ for the PHEP system (negative values indicate a decrease in $CO_2$ relative to initial C content, *i.e.* 13 $g.kg^{-1}$ dry matter) and this difference between these two systems was not significant. Cover crop biomasses were lower than expected (data not shown) in the L-GHG system, due both to the high frequency of very dry summers (in 2009 and 2012, total rainfall in August was 7 mm and 29 mm, respectively, whereas the 20-year mean value for rainfall in August was 51 mm) and the high degree of competition with weeds (data not shown). In addition, yields for spring field bean and winter oilseed rape (in 2014) were lower than expected (table 5, see explanations below). These crop residues did not, therefore, increase the C content of the soil.

### 3.1.3.2. Carbon balance of the four innovative cropping systems

Carbon balance did not differ significantly between the four systems ($p<0.05$, table 6). However, the similarities in carbon balance resulted from very different combinations of the two components of this balance: total greenhouse gas emissions and C sequestration. The proportions of the two components were almost identical for the L-GHG and PHEP systems. In the L-EN system, total greenhouse gas emissions were significantly lower (554 ± 107 $kgCO_2eq.ha^{-1}.year^{-1}$, $p<0.05$) than those of the L-GHG (1052 ± 183 $kgCO_2eq.ha^{-1}.year^{-1}$) and PHEP (1071 ± 145 $kgCO_2eq.ha^{-1}.year^{-1}$) systems, and were linked to significantly lower direct and indirect greenhouse gas emissions than for the other two systems ($p<0.05$, table 6). The significantly lower level of N fertilization in the L-EN system (19 ± 6 $kgN.ha^{-1}.year^{-1}$, $p<0.05$, table 3) than in the L-GHG (57 ± 13 $kgN.ha^{-1}.year^{-1}$) and PHEP (56 ± 11 $kgN.ha^{-1}.year^{-1}$) systems led to low direct and indirect $N_2O$ emissions (*i.e.* use over input manufacture). However, the low yields in the L-EN system resulted in small amounts of crop residues (table 5), leading, in turn, to a sharp decrease in C sequestration. The performance of the L-EN system was thus poorer than that of the L-GHG and PHEP systems. The No-Pest system had intermediate total greenhouse emissions (844 ± 46 $kgCO_2eq.ha^{-}$

$^{1}$.year$^{-1}$ table 6). In this system, direct emission levels were high, due to four plowing and several tillage operations during the six-year crop sequence (table 3), but indirect emissions were low, due to the low N fertilizer requirements (low yield objectives close to those in organic systems, 4.7 t.ha$^{-1}$, table 5). In this system, intensive plowing practices (table 3) and the small amounts of crop residues due to low yields (table 5) both resulted in much lower levels of C sequestration (-560 ± 49 kgCO$_2$eq.ha$^{-1}$.year$^{-1}$).

#### 3.1.4. Other environmental performances

The values obtained for the various qualitative indicators were lowest for crop diversity indicators (ranging from 6.8, for the PHEP system, to 7.8 for the L-EN system), whereas the other environmental indicators reached values of at least 8.4 (table 7). The environmental targets may therefore be considered to have been achieved. These findings varied little between replicates.

The PHEP system generated significantly less N$_2$O (8.69 ± 0.16, $p<0.05$) than the L-EN system (9.17 ± 0.06), due to differences in the amounts of N fertilizer applied (see explanation above). The amount of nitrogen leached was very small in all systems (less than 10 kgN.ha$^{-1}$.year$^{-1}$), due to the small amounts of N fertilizer applied (table 3). In the cropping system currently used in Ile-de-France, the mean amount of N fertilizer applied was about 110 kgN.ha$^{-1}$.year$^{-1}$, whereas the mean amount of fertilizer applied in the PHEP system was 56 ± 11 kgN.ha$^{-1}$.year$^{-1}$. Furthermore, careful adjustment of N application dates according to plant N requirements (not shown in table 3) and/or regular soil cover with plants or crop residues over time (*i.e.* catch or cover crops present most of the time between main crops, resulting in only short periods of bare soil) could explain these results.

The values of all pesticide indicators were greater than 8. These results were generally consistent with the TFI values obtained. However, it is difficult to explain the small differences between the innovative systems. The main findings were the significantly higher scores for the No-Pest system ($p<0.05$) and the low level of variability between the replicates of each innovative system.

## 3.2. Yield

### 3.2.1. The PHEP system

Yield objectives (table 5) were regularly achieved, for all crops except winter faba bean (mean decrease in yield of almost 50%: 1.45 ± 0.31 t.year$^{-1}$ versus 3.0 t.year$^{-1}$ expected), and were even higher than expected for winter oilseed rape (higher yields than expected: 3.64 ± 0.29 t.year$^{-1}$ *versus* 2.8 t.year$^{-1}$ expected). During the first three years of the field assessment, very long cold winter periods destroyed many legume plants and delayed growth in the spring, thereby decreasing potential yield (*i.e.* in 2009, 2010 and 2011 10-day minimum temperatures from the beginning of December to the end of February, were -7.23°C, -5.2°C and -2.4°C respectively, whereas the mean 10-day minimum temperature calculated over a 20-year period was systematically above 0°C. In 2009, 2010 and 2011, 10-day minimum temperatures below 0°C were observed from 1/12/2008 to 20/02/2009, from 10/12/2009 to 10/02/2010 and from 01/12/2010 to 30/01/2011). No-till practices may also decrease potential yield, consistent with the results obtained for the L-EN system (3.11 ± 0.97 $t.year^{-1}$). In this system, winter faba bean yields in replicates 1 (2.88 $t.year^{-1}$) and 3 (2.28 $t.year^{-1}$) were much lower than those in replicate 2 (4.16 $t.year^{-1}$), in which plowing took place (in 2009, all the plots of the L-EN system were plowed, to homogenize soil structure in the trial).

**3.2.2. The No-Pest system**

Winter wheat yields were systematically higher than expected (6.38 ± 1.47 $t.year^{-1}$ and 6.40 ± 0.36 $t.year^{-1}$ rather than the 4.7 $t.year^{-1}$ expected), due to the low pest pressure over this period as a result of specific climatic conditions (*i.e.* very long cold winters in four of the six years and very dry conditions in spring in 2009 and 2011), resulting in an absence of disease outbreaks in spring (http://agriculture.gouv.fr/bulletins-de-sante-du-vegetal). Hemp yields were both very high and variable (11.23 ± 2.65 $t.year^{-1}$ *versus* 8.0 $t.year^{-1}$ expected), highlighting the underestimation of the target to be attained in a region without relevant references, and improvements in crop management over time.

**3.2.3. The L-EN system**

In the L-EN system, the yields of winter wheat, sown after winter faba bean, were higher than expected (6.46 ± 0.51 $t.year^{-1}$ *versus* 5.4 $t.year^{-1}$ expected), due to optimal use of the N provided by this legume (the objective yields for faba bean were achieved, see above), in conditions in which small amounts of N fertilizer were applied. Yield varied considerably between replicates for winter wheat following flax (4.40 ± 1.45 $t.year^{-1}$). The lowest yield obtained for winter wheat, sown after flax (yield of 0.8 $t.ha^{-1}$ in replicate 3, table 5), resulted from high levels of competition with white clover and weeds (data not shown). The high levels of herbicide use on both flax and winter wheat (six and three applications on these two crops, respectively, table 3) reflect the high degree of weed development.

### 3.2.4. The L-GHG system

Yield goals were not always reached, but the results obtained differed between crops. Winter wheat yields were higher than expected (7.38 ± 015 t.year$^{-1}$ *versus* 6.7 t.year$^{-1}$ expected), whereas spring faba bean yields were much lower than anticipated (*i.e.* 66% lower than the target yield on average, 1.36 ± 0.71 t.year$^{-1}$ *versus* 4.1 t.year$^{-1}$ expected). These low yields reflected severe black aphid attacks in 2011 (*i.e.* 0.61 t.ha$^{-1}$, replicate 3, http://agriculture.gouv.fr/bulletins-de-sante-du-vegetal). Moreover, no-till practices are also known to reduce yield. In the L-GHG and No-Pest systems (*i.e.* without and with plowing, respectively, table 3), spring faba bean yields were 1.36 ± 0.71 t.year$^{-1}$ and 2.41 ± 1.98 t.ha$^{-1}$, respectively. Winter oilseed rape yields varied considerably between years (2.43 ± 2.14 t.year$^{-1}$), with the lowest value obtained for 2014 (*i.e.* 0 t.ha$^{-1}$, replicate 1). In our trial conditions, no-plow practices over a six-year period led to a gradual increase in the weed population (data not shown), resulting in an increase in herbicide use (one, two, two, three, and four herbicides used per year in 2009 to 2014, respectively; table 3). In the face of such weed competition, winter rapeseed was cut at the flowering stage in 2014.

### 3.2.5. Impact of particular annual weather conditions and role of the crop preceding the trial

Weather conditions explained some low yields in the innovative systems: in 2009. Low yields for maize in both the No-Pest (replicate 1, 3.81 t.year$^{-1}$ *versus* 5.6 t.year$^{-1}$ expected) and L-GHG (replicate 3, 5.27 t.year$^{-1}$ *versus* 7.0 t.year$^{-1}$ expected) systems were linked to a very dry summer period (*i.e.* in July and August 2009, 44 mm of rainfall: calculated during a period for which the 20-year mean was 114 mm; https://donneespubliques.meteofrance.fr/); in 2012, the lowest yield of flax (replicate 2, 0.86 t.year$^{-1}$ *versus* 1.6 t.year$^{-1}$ expected) resulted from a very cold period in February (*i.e.* during the first 10 days of February 2012, the mean minimum temperature was -5.5°C; the 20-year mean minimum temperature for the corresponding period was 4.8°C) that required a second sowing (*i.e.* of spring flax). In the L-EN system, the high spring oat yield in replicate 2 (6.06 t.year$^{-1}$ *versus* 3.2 t.year$^{-1}$ expected) resulted from a combination of very good weather conditions, low pest pressure (http://agriculture.gouv.fr/bulletins-de-sante-du-vegetal) and high nitrogen availability due to the earlier sowing of a legume catch crop (*i.e.* data not shown). Variability may also be linked to features specific to the trial: the sowing of winter barley as the prior crop in 2008 led to the development of winter wheat root disease (*i.e.* *Gaeumannomyces graminis*, data not shown) in the No-Pest system, replicate 3 (6.38 ± 1.47 1.6 t.year$^{-1}$), in 2009.

### 3.2.6. Variability over time

Yields were fairly stable in the PHEP, L-EN and No-Pest systems. By contrast, in the L-GHG system, yields reached expected levels in the first four years of the crop sequence, but were lower in the last two years (*e.g.* for oilseed rape in replicate 1: 0.00 $t.year^{-1}$ *versus* 2.8 $t.year^{-1}$ expected). Both large increases in the weed population and changes in soil structure (data not shown) due to an absence of plowing gradually reduced crop yields in our field conditions.

### 3.3. Economic results

Gross margins were highest for the PHEP (757.0 ± 88.7 $€.ha^{-1}.year^{-1}$), No-Pest (701.4 ± 48.4 $€.ha^{-1}.year^{-1}$) and L-GHG (619.6 ± 77.3 $€.ha^{-1}.year^{-1}$) systems (table 8). Furthermore, gross margins were significantly higher for the PHEP system than for the L-EN system (606.4 ± 56.1 $€.ha^{-1}.year^{-1}$, $p<0.05$). The similar results obtained for the L-GHG and L-EN systems resulted from different combinations of gross outputs and total variable costs. In the L-GHG system, high total variable costs (567.7 ± 29.7 $€.ha^{-1}.year^{-1}$) counteracted the high gross output (861.9 ± 84.0 $€.ha^{-1}.year^{-1}$). In the L-EN system, both gross output (696.0 ± 74.5 $€.ha^{-1}.year^{-1}$) and total variable costs (415.0 ± 46.7 $€.ha^{-1}.year^{-1}$) were lower than in any other system because (i) less N fertilizer was applied than in the PHEP and L-GHG systems, (ii) the no-till practices resulted in lower levels of fuel consumption and machinery use than for the No-Pest system, which was characterized by several plowing and tillage operations over the course of the crop sequence (table 3). The gross margin of the No-Pest system was one of the highest (701.4 ± 48.4 $€.ha^{-1}.year^{-1}$), due to hemp and winter wheat yields both being higher than expected (table 5).

### 3.4. Performance comparisons between the prototype systems and the field trial assessments

For the four innovative systems, most environmental performance indicators (total GHG emissions, total energy consumption, energy output, energy efficiency) and gross margins were close to the predictions of *ex ante* assessments (figure 1). The specific environmental constraints of the No-Pest and L-EN systems were almost satisfied. TFI, TFIH and "TFIothers" in the No-Pest system, and total energy consumption in the L-EN system closely matched expectations. For the L-GHG system, total greenhouse gas emissions were as projected, whereas C sequestration levels were much lower than expected.

A comparison of *ex ante* and *ex post* assessments showed large differences for TFI, TFIH and "TFIothers" (figure 1). In the L-GHG and L-EN systems, herbicide applications were underestimated in the prototype systems, and TFIH was four times higher for the L-GHG, and two times higher for the L-EN in the field assessments than estimated for the prototypes. TFIH was also higher than expected in the PHEP system, but to a lesser extent. During the design process, "TFIothers" was systematically overestimated because it could not take into account the specific low pest pressures occurring over the 2009-2014 period. For each innovative system, the energy output results measured in field conditions were very close to the expected values.

### 3.5. Performance comparisons between the innovative cropping systems subject to constraints and the PHEP system, taken as the reference system

The PHEP system performed particularly well, so the three constraint-limited systems performed poorly by comparison (figure 2). In both the L-GHG and L-EN systems, TFI, TFIH and "TFIothers" were higher than those calculated for the PHEP system (see the explanations above). However, these two systems under constraints differed for other performances. Most environmental performances were similar for the L-GHG and PHEP systems, whereas the L-EN system outperformed the reference system. In both the L-GHG and L-EN systems, gross margins were lower than those in the PHEP system, due to lower yields (table 5). This was unexpected for the L-GHG system, but was anticipated at the design step for the L-EN system (*i.e.* this system was designed with a target yield 20% lower than that of the PHEP system, to satisfy the energy constraint; Colnenne-David and Doré, 2015a). For a similar gross margin, pesticide indicator performances in the No-Pest system were much better than those in the PHEP system, but were associated with poor direct energy and C balance performances.

### 3.6. Performance comparisons between the innovative systems implemented in the field trial and the current system in the Ile-de-France region

Comparison between the four innovative systems and the current system in the Ile-de-France region (figure 3) demonstrated that all environmental performances were better in the innovative systems (*i.e.* all ratios below 1) than in the current system. Moreover, despite the lower energy outputs of the new systems than of the current system, gross margins were similar or slightly higher in the new systems than in the current Ile-de-France system. However, in the L-EN and No-Pest systems, TFIH and direct energy consumption, respectively, were similar to those for the current system (*i.e.* ratio values close to 1).

## 4. Discussion

### 4.1. Achievement of a multiplicity of objectives

We were able to design and implement the PHEP system, the environmental performances of which were better than those of the current system in the region, with no decrease in gross margin. The absence of pesticide use in the No-Pest system did not reduce gross margin either (the lower target yield resulted in an absence of impact on yield performance in our trial), but improved environmental performance (low greenhouse gas emissions, high energy use efficiency, low nitrate leaching). However, higher levels of direct energy consumption, linked to the high frequency of tillage practices, resulted in lower levels of C sequestration. It was possible to decrease energy consumption in the L-EN system only with a decrease in yield, resulting in a lower gross margin, and low levels of C storage in the soil. However, with the exception of the herbicide indicator, most of the environmental performances were fine. The management of agronomic strategies in the L-GHG system led to high yield variability, with a low economic impact. All environmental performances were satisfactory, with the exception of the herbicide use indicator, which was similar to that for the current system in the region.

As discussed in previous studies (Colnenne-David and Doré, 2015a), the various targets set for innovative systems can be antagonistic. The imposition of strong environmental constraints modified the performances of the constrained systems. Some performances deteriorated. In both the L-GHG and L-EN systems, no-plow practices led to higher levels of herbicide use to destroy cover crops and weeds (high TFIH), as previously reported by Zetner *et al.* (2004), Moreno *et al.* (2011), and Soane *et al.* (2012). In the L-EN system, lower levels of energy consumption, due to both no-till practice and low levels of N fertilization, were associated with 20% lower yields. In the No-Pest system, the absence of pesticide use had an adverse effect on SOM and yield. Decreases in the frequency of tillage and target yields resulted in much lower levels of C sequestration. Conversely, some environmental performances were significantly improved by the imposition of a severe environmental constraint. In both the L-EN and No-Pest systems, gas balance and energy efficiency were as high as those in the reference PHEP system. Economic comparisons with published findings were difficult, because the prices of both inputs and outputs depend on the country concerned, the period analyzed and the cropping system used (organic farm produce is sold at higher prices than the products of conventional agriculture). We then compared the gross margins of the innovative systems and the current system in Ile-de-France, in one price context: gross margins were slightly lower than those of the regional system for the L-GHG and L-EN systems, and slightly higher for the other new systems. However, this initial assessment did not take into account the contribution of product quality to farm-gate price, which is potentially higher for free-pesticide seeds, and the existence of specific markets for crops such as hemp.

It was difficult to meet the energy constraint in the L-EN system and environmental performances were less satisfactory (specifically for herbicide use) than in the PHEP system. It was not possible to satisfy the greenhouse gas constraint in the L-GHG system. For this system, during the design step, a clear hierarchy between the two sub-objectives (*i.e.* to enhance carbon sequestration first and then to reduce $N_2O$ emissions) were defined. In our field conditions, this strategy was not effective. Biomass production was low (see the above comments for yields) and resulted in lower levels of carbon storage than expected. Moreover, the amount of N fertilizer required to produce the expected biomass did not differ between the L-GHG and PHEP systems (*i.e.* total greenhouse gas emissions did not differ significantly between these two systems, table 6). After the first crop rotation, another design step was required to improve the L-GHG system, and a new combination of agricultural practices is currently being assessed in the field. The environmental results of the PHEP system were also very good, making it difficult to achieve both the energy goal in the L-EN system and the greenhouse gas target in the L-GHG system.

### 4.2. Difficulties implementing innovative systems with multiple goals in the field

Overall, the predictive capacity of *ex ante* assessment was good. However, discrepancies between the estimated performance of prototype systems and trial results, with some goals not achieved or the occurrence of unexpected environmental conditions, highlighted the difficulties involved in managing such systems in the field. We investigated the reasons for these differences, by analyzing agronomic practices, which we classified into four groups. Group 1: the chosen agronomic strategies were unsuitable for achieving the goals set. For example, in the L-GHG system, the absence of plowing did not lead to an increase in C sequestration. Group 2: some practices were unable to satisfy multiple goals simultaneously. For example, in the No-Pest system, the restitution of small amounts of organic matter, due to low yields, combined with regular plowing, which was required to manage weed populations, had an adverse effect on C sequestration. Group 3: some of the planned practices may not have been appropriate in field trial conditions. For example, despite the setting of TFI targets based on local experimental results obtained over a 10-year period, the "TFIothers" and TFIH values obtained did not match expectations. During the design process, pest occurrence rates were overestimated, resulting in higher levels of pesticide use estimated for the prototypes than actually applied in the field, except for the No-Pest system (http://agriculture.gouv.fr/bulletins-de-sante-du-vegetal, see the explanations above). Group 4: an unpredicted change occurred in the agrosystem. For example, weed levels were higher after flax in the L-EN system, resulting in higher levels of herbicide use than anticipated in several years (table 3). Similarly, weed populations increased throughout the crop sequence in the L-GHG system, resulting in larger slug populations (data not shown). Despite two molluscicide applications in 2014, oilseed rape was sown twice with no final yield (*i.e.* in 2014, yield was 0.00 t.ha$^{-1}$; in replicate 1, table 5). This classification highlighted the need for more time to eliminate technical uncertainties and to improve the management of innovative systems, to prevent the technical problems observed here (sowing failure, bad weed management in no-till systems). Moreover, the use of a broad range of tools should make it possible to improve the predictive capacity of *ex ante* assessment.

### 4.3. Comparison of performances with published results

#### 4.3.1. Energy consumption

The total energy consumption per hectare of the innovative systems was similar to that reported by Zentern *et al.* (2004) for different winter wheat-based crop sequence plow practices, and by Planche *et al.* (2015) for different cropping systems designed to meet specific environmental goals and assessed in France. As shown by Zentern *et al.* (2004) and regularly confirmed by different authors (Dumaski *et al.,* 2006; Rothke *et al.,* 2007; Morano *et al.,* 2011), the reduction of energy consumption due to no-till practices was generally offset by an increase in herbicide use. A similar pattern was observed when the energy performances of the PHEP and L-GHG systems were compared. The contribution of N fertilization to the overall energy consumption of the new systems was similar to that calculated for conventional, minimum tillage and no-till systems by Zentner *et al.* (2004), Rothke *et al.* (2007) and Moreno *et al.* (2011). Nevertheless, the energy consumption of an "integrated" system, such as that described by Nemecek *et al.* (2011b), with similar amounts of applied nitrogen to the PHEP system, was significantly greater than that calculated for the PHEP system. However, more details of the practices used in the Swiss "integrated" system, and of the references used for energy calculations, are required to analyze this discrepancy. By contrast, the energy consumption of the No-Pest system due to chemical fertilization was greater than that for organic systems using organic fertilizers (Morano *et al*., 2011; Nemecek *et al*., 2011a).

#### 4.3.2. GHG emissions

Goglio *et al.* (2014) used a combination of LCA and ecosystem modeling to assess GHG emissions in innovative systems. Over the 2009-2012 period, global warming potential (GWP) was 1.36 to 4.25 kgCO$_2$eq.ha$^{-1}$ in the PHEP system. Brentrup *et al.* (2004b) reported GWP ranges of 0.29 to 4.10 kgCO$_2$eq.ha$^{-1}$ for wheat with different amounts of N fertilizer, and Charles *et al.* (2006) reported a value of 2.42 kgCO$_2$eq.ha$^{-1}$ for the same crop. With a range of 2.15 to 5.03 kgCO$_2$eq.ha$^{-1}$, the estimates for the Swiss "integrated" and organic systems involving cereals

(Nemecek *et al.*, 2011b) were slightly higher than those for the PHEP system. Despite the high variability of these results, all the GWP results obtained were of the same order of magnitude. Since 2013, new cropping systems with multiple goals, including lower levels of tillage, have been assessed in field trials (Planche *et al.,* 2015). The annual GHG results calculated with the GES'TIM database (2010) ranged from 1340 to 2060 $kgCO_2eq.ha^{-1}.year^{-1}$. Despite the use of different methodologies (calculation of GHG emissions at the crop sequence scale in the innovative systems), the lowest value was close to that for the PHEP system (1071 $kgCO_2eq.ha^{-1}.year^{-1}$).

There is some debate about the degree to which no-till practices can increase soil organic carbon (SOC) sequestration relative to conventional tillage. Conservation tillage practices, with an absence of tillage and permanent soil cover, are adopted to limit the decline in SOC levels (Jonhson *et al.,* 2007; Smith *et al.*, 2008; Luo *et al.,* 2010). However, Dimassi *et al.* (2014) and Virto *et al.* (2012) have shown that the C input from crop residues is the major factor significantly correlated with differences in SOC levels between no-till and inversion tillage systems. Moreover, the SOC initially present modifies the rate of mineralization of soil biogeochemical components. Initial SOC content was 31 $tC.ha^{-1}$ in the trials managed by Li *et al.* (2005), 35 $tC.ha^{-1}$ in the study by Andriulo *et al.* (1999) and 42-45 $tC.ha^{-1}$ in that by Dimassi *et al.* (2014). The C sequestration process was complex, due to interaction between tillage practices and the amount of crop residue present. In the No-Pest system, low levels of C sequestration may be linked to both the small amounts of crop residues left on the soil and intensive plowing practices during the crop sequence (table 3), consistent with current scientific knowledge. However, in the L-EN system, in which only small amounts of crop residues were present, the no-till practices did not prevent C sequestration from being very low. Likewise, C sequestration did not differ significantly between the PHEP and L-GHG systems, despite large differences in tillage practices (table 3). Moreover, in the other studies, assessments were carried out over longer periods than this study. Dimassi *et al.* (2014) analyzed SOC evolution after 12 years of no-till practice. Bremer *et al.* (2008) measured changes in SOC 12 years after the introduction of fallow. The impacts of different tillage practices on C sequestration were assessed over 27- and 30-year periods by Liu *et al.* (2009) and Ghangsen Li *et al.* (2005), respectively. However, our results, simulated with the Simeos® tool, require validation with trial measurements. They were obtained after the first complete crop sequence (*i.e.* 5 to 6 years), which may be too short for the analysis of C sequestration. At least another full crop sequence may be required for a reliable analysis of changes in SOC. In organic systems, SOC content is generally reported to be higher than that in conventional systems, due to the use of organic fertilizers (Clark *et al.*,1998; Wells *et al.,* 2000; Azeez G., 2008; Mancinelli *et al.*, 2010). The significant difference, by a factor of about five, between the No-Pest and PHEP systems, may be explained by the many plowing operations and lower yields in the No-Pest system than in the PHEP system, and by the removal of hemp straw.

### 4.3.3. Yield performances

The target yields of the innovative systems were lower than those of conventional systems in the Ile-de-France region, to make it possible to satisfy environmental targets. Yields in the PHEP system were 5% to 10% lower than those of current systems, depending on the species considered, but gross margins were similar. Over the 2009-2013 period, mean winter wheat yield was 9.77 t.ha$^{-1}$ for a conventional system (Colnenne-David *et al.*, 2015b) assessed in a field trial located near Grignon (Debaeke *et al.,* 2009), whereas mean winter wheat yield was 8.56 t.ha$^{-1}$ in the PHEP system. The corresponding TFIs were 4.64 and 1.85 and the amount of N fertilizer applied was 147 kgN.ha$^{-1}$.year$^{-1}$ and 56 kgN.ha$^{-1}$.year$^{-1}$, respectively. The energy output of the innovative systems, with a range of 71 to 103 GJ.ha$^{-1}$.year$^{-1}$ for the L-EN and No-Pest systems, respectively, was lower than that of conventional systems in the Ile-de-France region (114 GJ.ha$^{-1}$.year$^{-1}$). Variable energy output results have been reported for conventional and organic systems (Klimekova *et al.*, 2007; Moreno *et al.,* 2011) from different locations and with different methodologies (different ways of taking straw energy into account). In all studies, energy output was systematically higher in conventional than in organic systems, contrasting with the results for the PHEP and No-Pest systems (96 and 103 GJ.ha$^{-1}$.year$^{-1}$, respectively). The high score of the No-Pest system resulted from both high crop productivity, particularly for hemp, which had a mean yield of 11.23 t.ha$^{-1}$, and high calorific value. Without hemp in the crop sequence, energy output would probably reach about 87 GJ.ha$^{-1}$.year$^{-1}$. The energy use efficiency of the new systems ranged from 12.1 to 13.7, and was thus much higher than published values. The EUE of the current Ile-de-France system was 7.75; those for conventional and organic systems were 6.55 and 6.41, respectively, over an 11-year period in Bulgaria (Bochu *et al.,* 2008) and 7.77 and 10.57, respectively, over a six-year period in Poland (Klimekova *et al.,* 2007). These high performances reflect a significant optimization of agronomic practices, in terms of both plowing and N fertilizer management. Moreover, the specific climatic conditions prevailing in the 2009-2014 period resulted in high yields with little or no pesticide application.

## 5. Conclusion

We show here that it is possible to design and implement innovative cropping systems with multiple goals combining environment performance and economic results. However, some of these goals appear to be more easily attainable than others. In our conditions, and during the first full crop sequence in the innovative systems, the application of a constraint imposing an absence of pesticide use did not result in poorer environmental and economic results that were obtained with the PHEP system, despite the strong performance of the PHEP system. However, our efforts to halve GHG emissions failed, due to the use of an inadequate strategy, which was nevertheless based on the knowledge available at the design stage. Increasing numbers of studies of the effects of agricultural practices on L-GHG emissions and carbon storage are being published, and their findings should make it possible to refine our strategy on the basis of cutting-edge knowledge. The L-EN system was moderately successful. It performed well, but did not quite achieve the targets set, and environmental performances were declining over time, suggesting a need for adaptation of the strategy. We are currently carrying out assessments for the second complete crop sequence in the same field trial (1) to validate the preliminary results for the PHEP and No-Pest systems, for which agricultural practices have been kept the same as in the first crop sequence, and (2) to assess the performances of new prototypes of the L-EN and L-GHG systems, which have been modified to decrease herbicide use, and to make it easier to satisfy the GHG constraint of the L-GHG system. We believe that such agronomic studies, combining *in silico* loops with field trials, are important and will facilitate the design of new innovative cropping systems to deal with the range of issues faced by agriculture.

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**Figure 1.** Multicriteria assessment of the four innovative cropping systems. Comparisons between *ex post* and *ex ante* assessments (the gray area corresponds to the *ex post* / *ex ante* ratio). Cropping systems: A: PHEP (productive with high environmental performance), B: L-GHG (low greenhouse gas emissions), C: L-EN (low energy use), and D: No-Pest (no pesticide use). Cg balance: carbon gas balance. C seq: carbon sequestration. Tot GHG: total greenhouse gas emissions. Tot En: total energy consumption. En op: energy output. En eff: energy efficiency. TFI: treatment frequency index. TFIH: TFI for herbicides. TFIothers: TFI for all pesticides other than herbicides. G margin: gross margin. Dotted lines indicate a score of 1: *ex post* system = *ex ante* system.

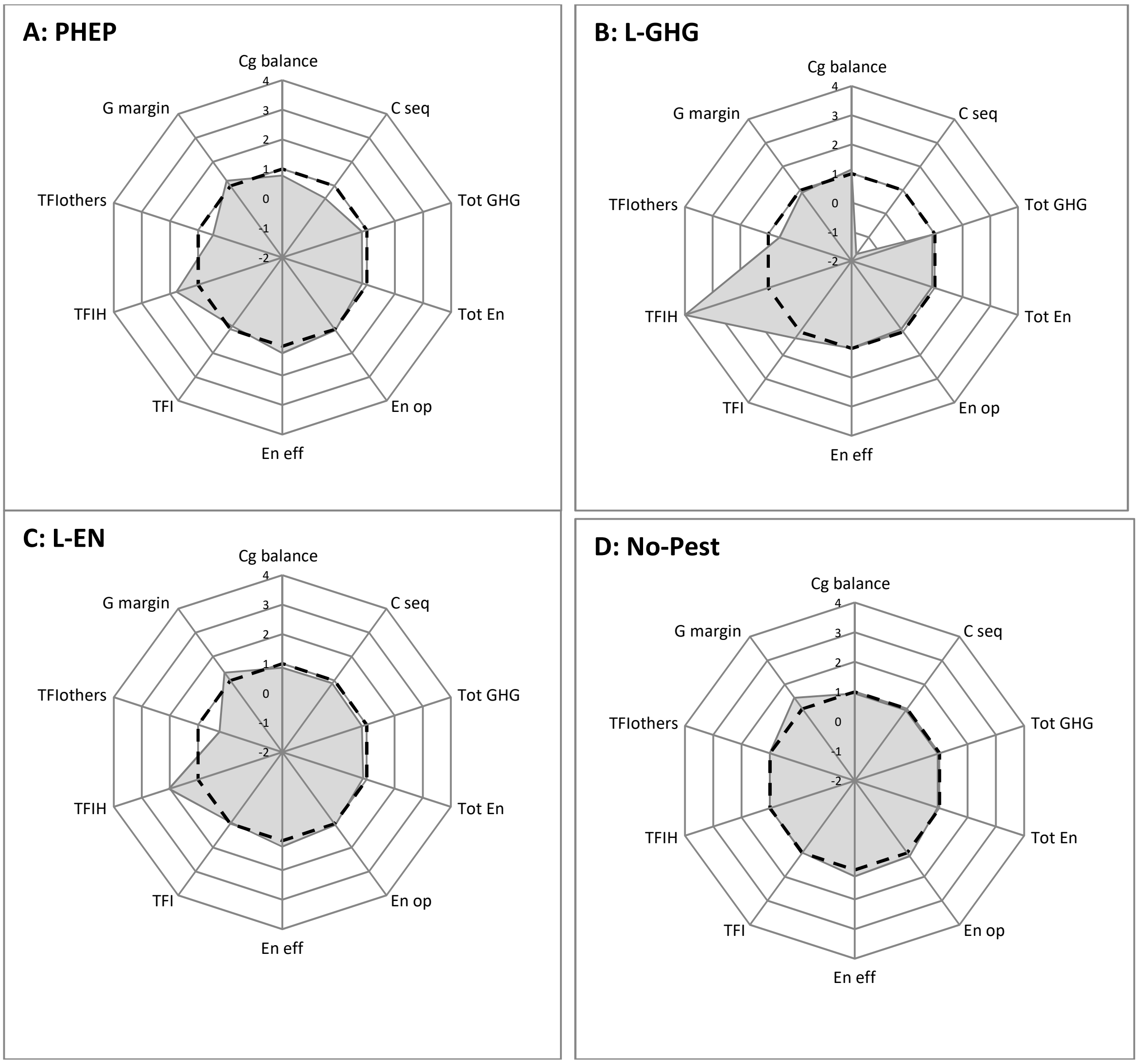

**Figure 2.** Multi-criteria assessment of the four innovative cropping systems. Comparisons between the three constraint-limited innovative systems and the PHEP system (the gray area corresponds to the constrained system/PHEP system ratio). Cropping systems: PHEP (productive with high environmental performance), L-GHG (low greenhouse gas emissions), L-EN (low energy use) and No-Pest (no pesticide use). Cg balance: carbon gas balance. Tot GHG: total greenhouse gas emissions. D GHG: direct greenhouse gas emissions. Ind GHG: indirect greenhouse gas emissions. Tot En: total energy consumption. D En: direct energy consumption. Ind En: indirect energy consumption. En op: energy output. EN eff: energy efficiency. TFI: treatment frequency index. TFIH: TFI for herbicides. TFIothers: TFI for all pesticides other than herbicides. G margin: gross margin. Dotted lines indicate a score of 1: constrained system = PHEP system.

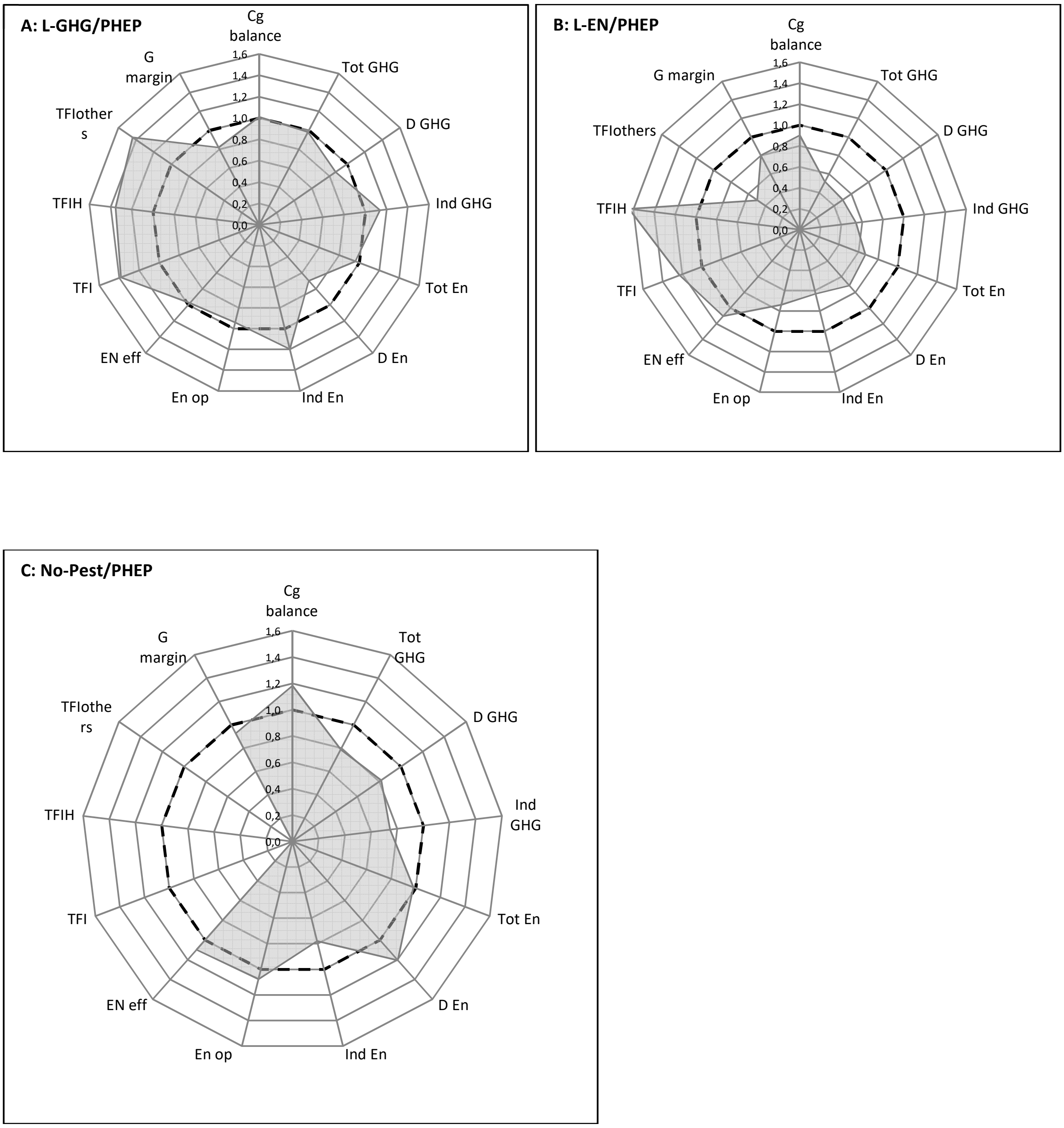

**Figure 3.** Multi-criteria assessment of the four innovative cropping systems. Comparisons between the four innovative systems and the current system in the Ile-de-France region (the gray area corresponds to the innovative system/current Ile-de-France system ratio. Cropping systems: A: PHEP (productive with high environmental performance), B: L-GHG (low greenhouse gas emissions), C: L-EN (low energy use) and D: No-Pest (no pesticide use). Cg balance: carbon gas balance. Tot GHG: total greenhouse gas emissions. D GHG: direct greenhouse gas emissions. Ind GHG: indirect greenhouse gas emissions. Tot En: total energy consumption. D En: direct energy consumption. Ind En: indirect energy consumption. EN op: energy output. TFI: treatment frequency index. TFIH: TFI for herbicides. TFIothers: TFI for all pesticides other than herbicides. G margin: gross margin. Dotted lines indicate a score of 1: innovative system = current Ile-de-France system.

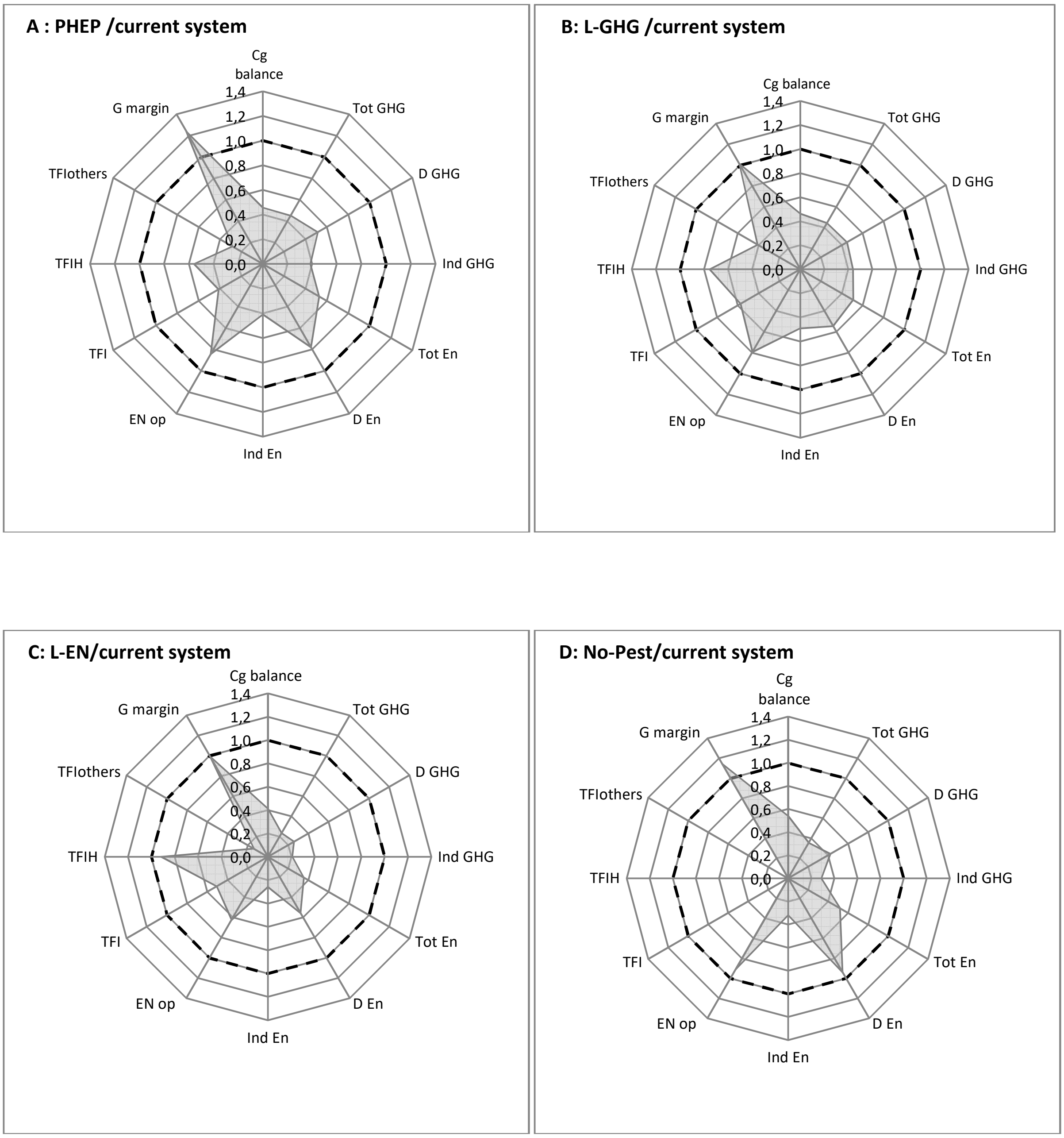

Table 1. Main crop management strategies used in the four cropping systems to meet constraints and environmental objectives. Cropping systems: PHEP (productive with high environmental performance), L-GHG (low greenhouse gas emissions), L-EN (low energy use), No-Pest (no pesticide use). In bold: constraints set for the innovative systems.

| Cropping systems | Constraints and objectives of the systems | Specific agronomic practices managed in the innovative systems to reach the combination of targets specific to the system | Common agronomic practices managed in the four systems |
|---|---|---|---|
| PHEP | - No constraint<br>- Environmental objectives<br>- High yield | Earlier sowing of oilseed rape to maximize competition against weeds, and use of stale seed-bed techniques to increase weed emergence before sowing and to reduce herbicide use<br>Shallow plowing to maintain beneficial insects such carbides (slug predators) and to reduce molluscicide use<br>One plowing permitted during the five-year crop sequence, to reduce energy consumption<br>Target yield: similar to that of low-input cropping systems in the Ile-de France region | Lengthening of the crop sequence (five or six years) and sowing a wide range of crops to enhance crop diversity and to reduce the impact of pests on crops<br>Sowing of highly resistant varieties or variety mixtures to reduce the impact of diseases on crops<br>Lower sowing density and levels of N fertilization to decrease shoot biomass and disease developments<br>Sowing of a legume to reduce N fertilization needs (*i.e.* to |
| No-Pest | - **No pesticide use**<br>- Environmental objectives<br>- High yield | Alternate sowing of host and non-host plants or of spring and winter crops, to decrease pest pressure<br>Sowing winter wheat later to reduce insect impact during autumn (aphids)<br>Sowing species with rapid shoot growth, such as hemp and triticale, to increase competitiveness<br>Using stale seed-bed techniques to increase weed emergence before sowing<br>Shallow plowing to maintain beneficial insects such carbides (slug predators)<br>Use of *Trichogramma* parasitoid wasps against *Ostrinia nubilalis* on maize<br>Mechanical weeding<br>Lowering target yield and levels of N fertilizer to decrease pest impact<br>Target yield: lower than for the PHEP system, higher than those achieved in organic systems because chemical fertilizers were allowed | |

| | | | |
|---|---|---|---|
| L-EN | - **To halve energy consumption relative to the PHEP system**<br>- Environmental objectives<br>- High yield | Prohibition of plowing and use of a direct drilling system to reduce direct energy consumption<br>Inclusion of legumes and high N use efficiency species in the crop sequence to reduce N fertilization requirements (*i.e.* indirect energy consumption)<br>Target yield: 20% lower than for the PHEP system, to reduce N fertilization (*i.e.* indirect energy consumption) | reduce indirect energy consumption)<br>Sowing catch crops before spring crops, oilseed rape after legumes and prohibition of N fertilization during the autumn and winter, to decrease nitrogen leaching during these seasons.<br>Non-removal of crop residues, to stabilize soil organic matter levels |
| L-GHG | - **To halve greenhouse gas emissions relative to the PHEP system**<br>- Environmental objectives<br>- High yield | Sowing of many cereals and maintenance of continuous soil cover (with a cover crop), to generate large amounts of residues to increase soil organic matter content<br>Prohibition of plowing and use of a direct drilling system to reduce carbon mineralization<br>Sowing of legumes to reduce N fertilization (*i.e.* $N_2O$ emissions)<br>Systematic sowing of cover crop to reduce $NO_3^-$ availability and $N_2O$ emissions<br>Sowing of species with taproots to reduce soil compaction<br>Target yield: similar to that of the PHEP system | |

**Table 2.** Mean annual treatment frequency indices (TFI: all pesticides; TFIH: herbicides; TFI others: pesticides than herbicides) for the four cropping systems, calculated at the crop sequence scale. Cropping systems: PHEP (productive with high environmental performance), L-GHG (low greenhouse gas emissions), L-EN (low energy use), No-Pest (no pesticide use). The values in brackets are the confidence intervals *($p<0.05$)* for the three replicates. For the No-Pest system, all values are zero.

| Performances | PHEP | L-GHG | L-EN | No-Pest |
|---|---|---|---|---|
| TFI (ha$^{-1}$.year$^{-1}$) | [1.73 ; 2.15] | [2.56 ; 2.81] | [1.83 ; 2.93] | 0.00 |
| TFIH (ha$^{-1}$.year$^{-1}$) | [1.06 ; 1.41] | [1.49 ; 1.85] | [1.71 ; 2.36] | 0.00 |
| TFIothers (ha$^{-1}$.year$^{-1}$) | [0.47 ; 0.94] | [0.78 ; 1.25] | [0.03 ; 0.67] | 0.00 |

**Table 3.** Main agronomic practices of the four cropping systems, for each replicate and each crop. Bold characters correspond to the crops sown in 2009, *i.e.* the first crop of the crop sequence sown in each replicate. Rep = replicate. Nb = number. Catch or cover crops were systematically sown before main crops. W and S are winter and spring crops, respectively. MWheat or MBarley = mixture of varieties for wheat and barley, respectively. 2Oilseed rape or 2Maize = two sowings of oilseed rape or maize, respectively, due to plant emergence failure. Flax(W)+Flax(S) = sowing of spring flax after winter flax was destroyed by frost. None = no cover or catch crop. Bmustard and Wmustard correspond to brown and white mustard, respectively. Wclover = white clover. IntWheat = intercropped winter wheat and white clover. Cropping systems: PHEP (productive with high environmental performance), L-GHG (low greenhouse gas emissions), L-EN (low energy use), No-Pest (no pesticide use).

| Cropping systems Replication Crop sequence | Crop | Nb of plowings (P) and tillage(T) | Sowing density (kg seed.ha$^{-1}$) | Mineral nitrogen rate (kg.ha$^{-1}$) | Species of cover/catch crops before each crop or associated crop in intercropping | Nb of herbicides (H), fungicides (F), insecticides (I), and molluscicides (M) | Nb of mechanical weedings |
|---|---|---|---|---|---|---|---|
| PHEP<br>Rep1: **Barley(S)-**Faba bean(W)-Wheat(W)-Rape(W)-MWheat(W) | **Barley(S)** | 1P+1T | 154 | 40 | Bmustard | 1H | None |
| | Faba bean(W) | 1T | 162 | 0 | None | None | None |
| | Wheat(W) | 3T | 110 | 90 | None | 1H | None |
| | Rape(W) | 2T | 2 | 115 | None | 2H+1F+2I+1M | None |
| | MWheat(W) | 1T | 99 | 90 | None | 3H | None |
| PHEP<br>Rep2 **Wheat(W)-**Barley(S)-Faba bean(W)-Wheat(W)-Rape(W) | **Wheat(W)** | 1T | 122 | 40 | None | 1H | None |
| | Barley(S) | 1T | 112 | 70 | Wmustard | 1H | None |
| | Faba bean(W) | 1P | 212 | 0 | None | 3H | None |
| | Wheat(W) | 4T | 109 | 70 | None | 2H | None |
| | Rape(W) | 2T | 3 | 100 | None | 2H+1F+1I°1M | None |
| PHEP<br>Rep3 : **2Rape(W)-**Wheat(W)-Barley(S)-Faba bean(W)-Wheat(W) | **2Rape(W)** | 1T | 2+3 | 50 | None | 1H+1F+2I+1M | None |
| | Wheat(W) | 2T | 100 | 120 | None | 2H | None |
| | Barley(S) | 1P+1T | 127 | 60 | Wmustard | 2H | None |
| | Faba bean(W) | None | 342 | 0 | Buckwheat | 2H | None |
| | Wheat(W) | 2T | 104 | 0 | None | 2H+2F | None |
| L-GHG<br>Rep1<br>**Wheat(W)-**Barley(W)-2Maize -Triticale-Faba bean(S)-2Rape(W) | **Wheat(W)** | 1T | 122 | 40 | None | 1H | None |
| | Barley(W) | None | 127 | 80 | Peas | 1H | None |
| | 2Maize | 1T | 190 | 80 | Clover+Oat | 2H+1M | None |
| | Triticale | None | 205 | 0 | None | 2H+1F | None |
| | Faba bean(S) | None | 220 | 0 | Wmustard | 3H | None |
| | 2Rape(W) | None | 3+4 | 50 | None | 4H+2M | None |
| L-GHG<br>Rep2: **2Rape(W)-**Wheat(W)-Barley(W)-Maize-Triticale-Faba bean(S) | **2Rape(W)** | 1T | 2+3 | 50 | None | 1H+1F+2I+1M | None |
| | Wheat(W) | None | 137 | 80 | Peas | 2H | None |
| | Barley(W) | None | 184 | 80 | Peas | 4H | None |
| | Maize | 1T | 190 | 110 | Clover+Oat | 3H+1M | None |
| | Triticale | None | 165 | 90 | No | 1H | None |
| | Faba bean(S) | None | 248 | 0 | Lentil+Oat+Wmustard | 1H+1F+1M | None |
| L-GHG<br>Rep3: **Maize**-Triticale-2Faba bean(S)-Rape (W)-Wheat(W)-MBarley(W) | **Maize** | 1T | 190 | 130 | Bmustard | 1H+1I | None |
| | Triticale | None | 100 | 0 | None | 1H | None |
| | 2Faba bean(S) | None | 220+73 | 0 | None | 3H+1I+1M | None |
| | Rape (W) | None | 9 | 40 | None | 2H+1F+1I+1M | None |
| | Wheat(W) | None | 112 | 100 | Fenugreek | 4H+2H+1M | None |
| | MBarley(W) | None | 145 | 90 | Buckwheat | 3H | None |
| L-EN<br>Rep1 : **Flax(W)**-IntWheat(W)-Oat(W)-Faba bean(W)-Wheat(W) | **Flax(W)** | 1T | 33 | 0 | None | 1H | None |
| | IntWheat(W) | None | 125 | 40 | Wclover | 1H | None |
| | Oat(W) | None | 117 | 0 | Wclover | 3H | None |
| | Faba bean(W) | None | 342 | 0 | None | 4H | None |
| | Wheat(W) | None | 126 | 30 | None | 3H+1M | None |
| L-EN<br>Rep2: **Oat(S)-**Faba bean(W)-Wheat(W)-Flax(W)+Flax(S)-IntWheat(W) | **Oat(S)** | 1T | 114 | 0 | Wclover | 1H | None |
| | Faba bean(W) | None | 159 | 0 | None | None | None |
| | Wheat(W) | None | 142 | 40 | None | 4H | None |
| | Flax(W)+Flax(S | None | 35+60 | 0 | None | 5H | None |
| | IntWheat(W) | None | 124 | 90 | Wclover | 4H+1M | None |
| L-EN<br>Rep3: **Faba bean(W)-**Wheat(W)-Flax(W)-IntWheat(W)-Oat(S) | **Faba bean(W)** | 1T | 131 | 0 | None | None | None |
| | Wheat(W) | None | 125 | 0 | None | 2H | None |
| | Flax(W) | None | 40 | 0 | None | 6H | None |
| | IntWheat(W) | None | 173 | 80 | Wclover | 3H | None |
| | Oat(S) | None | 150 | 0 | Wclover | 2H | None |
| No-Pest<br>Rep1: **Maize-**MWheat(W)-Faba bean(S)-MWheat(W)-Hemp-Triticale | **Maize** | 1P+2T | 190 | 80 | Bmustard | None | 2 |
| | MWheat(W) | None | 235 | 70 | None | None | 1 |
| | Faba bean(S) | 1P+1T | 220 | 0 | Wmustard+Oat | None | 1 |
| | MWheat(W) | 3T | 160 | 0 | None | None | 1 |
| | Hemp | 1P | 57 | 30 | Vetch | None | 0 |
| | Triticale | 1P+1T | 141 | 30 | None | None | 1 |
| No-Pest<br>Rep2 : **Faba bean(S)-**MWheat(W)-Hemp- | **Faba bean(S)** | 1P+2T | 189 | 0 | None | None | 0 |
| | MWheat(W) | 1T | 156 | 0 | Barley volunteers | None | 1 |
| | Hemp | 1P+2T | 55 | 0 | Clover+Mustard | None | 0 |
| | Triticale | 3T | 160 | 40 | None | None | 0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Triticale-Maize- | Maize | 1P+1T | 190 | 90 | Wmustard+Lentil | None | 2 |
| MWheat(W | MWheat(W) | 1P | 160 | 70 | None | None | 1 |
| No-Pest | **Wheat(W)** | 2T | 174 | 0 | None | None | 0 |
| Rep3: **Wheat(W)-** | Faba bean(S) | 1P+2T | 196 | 0 | Buckwheat | None | 1 |
| Faba bean(S)- | MWheat(W) | 3T | 160 | 0 | None | None | 1 |
| MWheat(W)-Hemp- | Hemp | 1P+3T | 55 | 0 | Peas | None | 0 |
| Triticale-2Maize | Triticale | 1T | 150- | 0 | None | None | 1 |
| | 2Maize | 1P+3T | 220+220 | 110 | Mustard+Lentil | None | 5 |

**Table 4.** Energy (total, direct and indirect) consumption (MJ.ha$^{-1}$.year$^{-1}$), energy output (MJ.ha$^{-1}$.year$^{-1}$) and energy use efficiency of the four cropping systems. Cropping systems: PHEP (productive with high environmental performance), L-GHG (low greenhouse gas emissions), L-EN (low energy use), No-Pest (no pesticide use). The values shown are the means and the standard deviations for the three replicates. The same letters indicate homogeneous groups according to the Tukey test, *$p<0.05$* (ns: not significant).

| Performance | PHEP | L-GHG | L-EN | No-Pest |
|---|---|---|---|---|
| Total energy consumption (MJ.ha$^{-1}$.year$^{-1}$) | 7755 ± 711 a | 7459 ± 793 a | 5201 ± 502 b | 7604 ± 517 a |
| Direct energy consumption (MJ.ha$^{-1}$.year$^{-1}$) | 3665 ± 223 b | 2562 ± 235 c | 2618 ± 171 c | 4417 ± 425 a |
| Indirect energy consumption (MJ.ha$^{-1}$.year$^{-1}$) | 4090 ± 489 ab | 4897 ± 568 a | 2584 ± 479 c | 3187 ± 99 bc |
| Ratio: Indirect energy consumption/ Total energy consumption | 52.7% | 65.7% | 49.7% | 41.9% |
| Energy output (MJ.ha$^{-1}$.year$^{-1}$) | 95965 ± 8397 a | 90229 ± 5572 a | 70997 ± 9991 b | 103323 ± 3629 a |
| Energy use efficiency | 12.41 ± 1.07 (ns) | 12.14 ± 0.74(ns) | 13.71 ± 2.10 (ns) | 13.61 ± 0.54 (ns) |

**Table 5.** Annual yield ($t.ha^{-1}$) values (0% humidity) from 2009 to 2014, for each crop of the four cropping systems. Results in bold characters correspond to the crops sown in 2009 (i.e. the first crop of the crop sequence sown in each replicate). W and S are winter and spring crops, respectively. Cropping systems: PHEP (productive with high environmental performance), L-GHG (low greenhouse gas emissions), L-EN (low energy use), No-Pest (no pesticide use).

| Cropping system Replication | Successive crops in the crop sequence | | | | | |
|---|---|---|---|---|---|---|
| PHEP: species | S barley | W faba bean | W wheat | W rape | W wheat | |
| calorific value ($MJ.t^{-1}$) | 14.5 | 14.4 | 14.5 | 24.6 | 14.5 | |
| PHEP: target yield | 5.3 | 3.0 | 6.7 | 2.8 | 6.7 | |
| PHEP: Replicate 1 | **6.81** | 1.80 | 8.13 | 3.49 | 7.78 | |
| PHEP: Replicate 2 | 5.32 | 1.38 | 6.65 | 3.48 | **6.13** | |
| PHEP: Replicate 3 | 4.78 | 1.18 | 6.73 | **3.96** | 8.17 | |
| PHEP: mean yield value and standard deviation | 5.64 ± 1.04 | 1.45 ± 0.31 | 7.17 ± 0.81 | 3.64 ± 0.29 | 7.36 ± 1.12 | |
| L-GHG: species | W wheat | W barley | Maize | Triticale | S faba bean | W rape |
| calorific value ($MJ.t^{-1}$) | 14.5 | 14.5 | 14.5 | 14.6 | 14.4 | 24.6 |
| L-GHG: target yield | 6.7 | 6.1 | 7.0 | 6.0 | 4.1 | 2.8 |
| L-GHG: Replicate 1 | **7.40** | 6.15 | 7.64 | 5.82 | 1.95 | 0.00 |
| L-GHG: Replicate 2 | 7.51 | 4.94 | 7.46 | 5.53 | 1.53 | **4.04** |
| L-GHG: Replicate 3 | 7.24 | 4.96 | **5.27** | 6.99 | 0.61 | 3.26 |
| L-GHG: mean yield value and standard deviation | 7.38 ± 0.15 | 5.35 ± 0.72 | 6.79 ± 1.30 | 6.11 ± 0.79 | 1.36 ± 0.71 | 2.43 ± 2.14 |
| L-EN: species | S oat | W faba bean | W wheat | W flax | W wheat | |
| calorific value ($MJ.t^{-1}$) | 15.8 | 14.4 | 14.5 | 21.2 | 14.5 | |
| L-EN: target yield | 3.2 | 3.0 | 5.4 | 1.6 | 5.4 | |
| L-EN: Replicate 1 | 3.69 | 2.88 | 6.07 | **1.72** | 6.00 | |
| L-EN: Replicate 2 | **6.06** | 2.28 | 6.33 | 0.86 | 6.51 | |
| L-EN: Replicate 3 | 3.46 | **4.16** | 6.98 | 1.29 | 0.75 | |

| | | | | | | |
|---|---|---|---|---|---|---|
| L-EN: mean yield value and standard deviation | 4.40 ± 1.45 | 3.11 ± 0.97 | 6.46 ± 0.51 | 1.29 ± 0.40 | 4.42 ± 3.16 | |
| No-Pest: species | Maize | W wheat | S faba bean | W wheat | Hemp | Triticale |
| calorific value (MJ.t$^{-1}$) | 14.5 | 14.5 | 14.4 | 14.5 | 16.5 | 14.6 |
| No-Pest: target yield | 5.6 | 4.7 | 3.1 | 4.7 | 8.0 | 4.3 |
| No-Pest: Replicate 1 | **3.81** | 7.99 | 0.28 | 6.25 | 13.10 | 3.38 |
| No-Pest: Replicate 2 | 5.24 | 6.09 | **4.19** | 6.82 | 8.20 | 4.97 |
| No-Pest: Replicate 3 | 5.83 | **5.07** | 2.76 | 6.14 | 12.40 | 5.03 |
| No-Pest: mean yield value and standard deviation | 4.96 ± 1.03 | 6.38 ± 1.47 | 2.41 ± 1.98 | 6.40 ± 0.36 | 11.23 ± 2.65 | 4.46 ± 0.92 |

**Table 6.** Carbon balance, C sequestration and greenhouse gas emissions (total, direct and indirect) of the four cropping systems, calculated over a 50-year period (C content of the soil = 13 g.kg$^{-1}$ dry matter). Cropping systems: PHEP (productive with high environmental performance), L-GHG (low greenhouse gas emissions), L-EN (low energy use), No-Pest (no pesticide use). The values shown are the means and standard deviations for the three replicates. Identical letters indicate homogeneous groups according to the Tukey test, *$p < 0.05$* (ns: not significant).

| Performances | PHEP | L-GHG | L-EN | No-Pest |
|---|---|---|---|---|
| Carbon balance (kgCO$_2$eq.ha$^{-1}$.year$^{-1}$) | 1188 ± 270 ns | 1202 ± 86 ns | 1072 ± 29 ns | 1404 ± 90 ns |
| C sequestration (kgCO$_2$eq.ha$^{-1}$.year$^{-1}$) | -117 ± 150 a | -149 ± 117 a | -518 ± 92 b | -560 ± 49 b |
| Total greenhouse gas emissions (kgCO$_2$eq.ha$^{-1}$.year$^{-1}$) | 1071 ± 145 a | 1052 ± 183 a | 554 ± 107 b | 844 ± 46 ab |
| Direct greenhouse gas emissions (kgCO$_2$eq.ha$^{-1}$.year$^{-1}$) | 622 ± 82 a | 541 ± 102 a | 311 ± 40 b | 509 ± 26 a |
| Indirect greenhouse gas emissions (kgCO$_2$eq.ha$^{-1}$.year$^{-1}$) | 449 ± 64 ab | 511 ± 82 a | 243 ± 67 c | 335 ± 20 bc |

**Table 7.** Environmental performances of the various innovative cropping systems calculated with the Criter® tool, at the crop sequence scale. Cropping systems: PHEP (productive with high environmental performance), L-GHG (low greenhouse gas emissions), L-EN (low energy use), No-Pest (no pesticide use). For the $NH_3$ volatilization, $N_2O$ emissions and $NO_3^-$ leaching indicators, the values shown are the means and standard deviations for the three replicates. Identical letters indicate homogeneous groups according to the Tukey test, $p<0.05$ (ns: not significant). The Pesticide volatilization, Pesticide leaching, and Pesticide runoff indicators, all take a value of 10 for the No-Pest system. We therefore show confidence intervals in italic brackets (*$p<0.05$*). For the Crop diversity indicator, no standard deviations were calculated because the three replicates of each system had the same crop sequence.

| Indicators | PHEP | L-GHG | L-EN | No-Pest |
|---|---|---|---|---|
| Qualitative indicators | | | | |
| $NH_3$ volatilization | 9.84 ± 0.03 b | 9.85 ± 0.04 b | 9.94 ±.0.02 a | 9.91 ± 0.01 ab |
| $N_2O$ emissions | 8.69 ± 0.16 b | 8.80 ± 0.14 ab | 9.17 ± 0.06 a | 9.10 ± 0.13 ab |
| *Pesticide volatilization* | *[8.52 ; 9.72]* | *[8.22 ; 8.78]* | *[8.39 ;9.37]* | *10.00* |
| *Pesticide leaching* | *[8.37 ; 8.43]* | *[8.74 ;8.78]* | *[8.38 ;8.76]* | *10.00* |
| *Pesticide runoff* | *[8.59 ;9.10]* | *[8.69 ;8.90]* | *[8.72 ;9.02]* | *10.00* |
| Crop diversity | 6.8 | 7 | 7.8 | 7.5 |
| Quantitative indicator | | | | |
| $NO_3^-$ leaching ($kg\ NO_3^-.ha^{-1}.year^{-1}$) | 8.93 ± 2.24 a | 4.53 ± 0.56 b | 6.25 ± 0.67 ab | 7.83 ± 0.80 ab |

**Table 8.** Economic results (gross margin, gross output and total variable costs, all expressed in €.ha$^{-1}$.year$^{-1}$) for the various innovative cropping systems. CAP = Common Agricultural Policy. Cropping systems: PHEP (productive with high environmental performance), L-GHG (low greenhouse gas emissions), L-EN (low energy use), No-Pest (no pesticide use). The values shown are the means and standard deviations for the three replicates. Identical letters indicate homogeneous groups according to the Tukey test, $p<0.05$.

| Performances | PHEP | L-GHG | L-EN | No-Pest |
|---|---|---|---|---|
| Gross margin (€.ha$^{-1}$.year$^{-1}$) | 757.0 ± 88.7 a | 619.6 ± 77.3 ab | 606.4 ± 56.1 b | 701.4 ± 48.4 ab |
| Gross output (€.ha$^{-1}$.year$^{-1}$) | 929.1 ± 71.6 a | 861.9 ± 84.0 a | 696.0 ± 74.5 b | 879.0 ± 48.9 a |
| Total variable costs (€.ha$^{-1}$.year$^{-1}$) | 497.5 ± 43.8 ab | 567.7 ± 29.7 a | 415.0 ± 46.7 b | 503.0 ± 54.6 ab |
| CAP subsidies (€.ha$^{-1}$.year$^{-1}$) | 325 | 325 | 325 | 325 |